

ND and NB systems in quark delocalization color screening model

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Abstract The ND and NB systems with $I = 0$ and 1 , $J^P = \frac{1}{2}^\pm$, $\frac{3}{2}^\pm$, and $\frac{5}{2}^\pm$ are investigated within the framework of quark delocalization color screening model. The results show that all the positive parity states are unbound. By coupling to the ND^* channel, the state ND with $I = 0$, $J^P = \frac{1}{2}^-$ can form a bound state, which can be invoked to explain the observed $\Sigma(2800)$ state. The mass of the ND^* with $I = 0$, $J^P = \frac{3}{2}^-$ is close to that of the reported $\Lambda_c(2940)^+$, which indicates that $\Lambda_c(2940)^+$ can be explained as a ND^* molecular state in QDCSM. Besides, the ΔD^* with $I = 1$, $J^P = \frac{5}{2}^-$ is also a possible resonance state. The results of the bottom case of NB system are similar to those of the ND system. Searching for these states will be a challenging subject of experiments.

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1 Introduction

In the past decade, many near-threshold charmonium-like states have been reported by Belle, BaBar, BESIII, LHCb and other collaborations, which triggers lots of studies on the molecule-like hadrons containing heavy quarks. For example, the triplet of excited Σ_c baryons, $\Sigma_c(2800)$, was observed by Belle [1], and they tentatively identified the quantum numbers of these states

as $J^P = \frac{3}{2}^-$. The same neutral state Σ_c^0 was also observed in B decays by the BaBar collaboration with the mean value of mass higher by about 3σ from that obtained by Belle [2], although the widths from these two measurements are consistent. Moreover, a new charmed hadron $\Lambda_c(2940)^+$ with mass $M = 2939.8 \pm 1.3(\text{stat}) \pm 1.0(\text{syst}) \text{ MeV}/c^2$ and width $\Gamma = 17.5 \pm 5.2(\text{stat}) \pm 5.9(\text{syst}) \text{ MeV}/c^2$ was reported by BaBar collaboration by analyzing the $D^0 p$ invariant mass spectrum [3], and it is confirmed as a resonant structure in the final state of $\Sigma_c(2455)^{0,++}\pi^\pm \rightarrow \Lambda_c^+\pi^+\pi^-$ by Belle [4].

The experimental observations have stimulated extensive interest in understanding the structures of the states $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$. Since the $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ are near the threshold of ND and ND^* , respectively, many work treat them as candidates of molecular states. For the $\Sigma_c(2800)$, M. Lutz and E. Kolomeitsev interpreted it as a chiral molecule [5], while C. Jiménez-Tejero *et al.* found it was a dynamically generated resonance with a dominant ND configuration [6]. Y. B. Dong *et al.* estimated the strong $\Lambda_c\pi$ decays of the $\Sigma_c(2800)$ state for different spin-parity assignments by assuming a dominant molecular ND structure of the state and showed that the decay widths of $\Sigma_c \rightarrow \Lambda_c\pi$ were consistent with current data for the $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^-$ assignments [7]. Moreover, J. R. Zhang investigated $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ as the S -wave ND state with $J^P = \frac{1}{2}^-$ and ND^* state with $J^P = \frac{3}{2}^-$, respectively in the framework of QCD sum rules. The results showed that the masses of these two states were bigger than the experimental data, but the compact structure of the states could be ruled out [8]. For the $\Lambda_c(2940)^+$, X. G. He *et al.* proposed that it may be a $D^{*0}p$ molecular state with $J^P = \frac{1}{2}^-$ [9], while Y. B. Dong *et al.* showed the $\Lambda_c(2940)^+$ was a molecu-

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lar state composed of a nucleon and D^* mesons with $J^P = \frac{1}{2}^+$ by studying the decay widths of the strong two-body decay channels $\Lambda_c(2940)^+ \rightarrow pD^0$, $\Sigma_c^{++}\pi^-$ and $\Sigma_c^0\pi^+$ [10], and this conclusion was confirmed by investigating the width of the radiative decay process $\Lambda_c(2940)^+ \rightarrow \Lambda_c(2286)^+ + \gamma$ [11] and the strong three-body decay process $\Lambda_c(2940)^+ \rightarrow \Lambda_c(2286)^+\pi^+\pi^-$ and $\Lambda_c(2286)^+\pi^0\pi^0$ [12]. Moreover, J. He and X. Liu explained the $\Lambda_c(2940)^+$ as an isoscalar S -wave or P -wave D^*N system with $J^P = \frac{3}{2}^-$ or $J^P = \frac{1}{2}^+$ in the framework of the one-boson-exchange model [13]. And in Ref. [14], they found a possible molecular candidate with $J^P = \frac{3}{2}^-$ for the $\Lambda_c(2940)^+$. In addition, a bound state D^*N with $J^P = \frac{3}{2}^-$, which can be explained as the $\Lambda_c(2940)^+$, was also obtained in a constituent quark model [15]. In the work of Ref. [16], the total cross section of the $\pi^-p \rightarrow D^-D^0p$ reaction was calculated within an effective lagrangian approach, which indicated that the spin-parity assignment of $\frac{1}{2}^-$ for $\Lambda_c(2940)^+$ gave a sizable enhancement for the total cross section in comparison with a choice of $J^P = \frac{1}{2}^+$.

Another way to describe the states $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ is based on the assumption that they are conventional charmed baryons. A relativized potential model predicted that the masses of Σ_c^* with $J^P = \frac{3}{2}^-$ or $\frac{5}{2}^-$ and Λ_c^* with $J^P = \frac{3}{2}^+$ or $\frac{5}{2}^-$ are close to the value of $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$, respectively [17]. The strong decays of $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ as charmed baryons have been studied by using 3P_0 model [18], heavy hadron chiral perturbation theory [19], and chiral quark model [20]. Moreover, Ebert *et al.* suggested $\Sigma_c(2800)$ as one of the orbital ($1P$) excitations of the Σ_c with $J^P = \frac{1}{2}^-, \frac{3}{2}^-$ or $\frac{5}{2}^-$, and proposed $\Lambda_c(2940)^+$ as the first radial excitation of Σ_c with $J^P = \frac{3}{2}^+$ [21]. J. He *et al.* estimated the production rate of $\Lambda_c(2940)^+$ as a charmed baryon at PANDA [22]. H. Garcilazo *et al.* solved exactly the three-quark problem by means of the Faddeev method in momentum space, and showed that $\Sigma_c(2800)$ would correspond to an orbital excitation with $J^P = \frac{1}{2}^-$ or $\frac{3}{2}^-$, and the $\Lambda_c(2940)^+$ may constitute the second orbital excitation of the Λ_c baryon [23].

Although many theoretical explanations to $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ were proposed, the properties of these two states are still in ambiguous. Therefore, more efforts are needed to reveal the underlying structure of these two states. Quantum chromodynamics (QCD) is widely accepted as the fundamental theory of the strong interaction. However, the direct use of QCD for low-energy hadron physics, for example, the properties of hadrons, the nucleon-nucleon (NN) interaction, is still difficult because of the nonperturbative complications

of QCD. QCD-inspired quark models are still the main approach to study the hadron-hadron interaction.

It is well known that the forces between nucleons (hadronic clusters of quarks) are qualitative similar to the forces between atoms (molecular force). This similarity is naturally explained in the quark delocalization color screening model (QDCSM) [24], which has been developed and extensively studied. In this model, quarks confined in one nucleon are allowed to delocalize to a nearby nucleon and the confinement interaction between quarks in different baryon orbits is modified to include a color screening factor. The latter is a model description of the hidden color channel coupling effect [25]. The delocalization parameter is determined by the dynamics of the interacting quark system, thus allows the quark system to choose the most favorable configuration through its own dynamics in a larger Hilbert space. The model gives a good description of nucleon-nucleon and hyperon-nucleon interactions and the properties of deuteron [26]. It is also employed to calculate the baryon-baryon scattering phase shifts and the dibaryon candidates in the framework of the resonating group method (RGM) [27, 28]. Recently, it has been used to investigate the pentaquarks with heavy quarks, and the $P_c(4380)$ can be explained as the molecular pentaquark of Σ_c^*D with quantum numbers $IJ^P = \frac{1}{2}\frac{3}{2}^-$ in QDCSM [29].

In present work, QDCSM is employed to study the properties of ND systems, and the channel-coupling effect of ND^* , ΔD , and ΔD^* channels are included. Our purpose is to investigate whether $\Sigma_c(2800)$ and $\Lambda_c(2940)^+$ could be explained as a molecular state composed of a nucleon and D or D^* mesons. On the other hand, we also want to see if any other bound or resonance state exist or not. Extension of the study to the bottom case is also interesting and is performed here. The structure of this paper is as follows. After the introduction, we present a brief introduction of the quark model used in section 2. Section 3 devotes to the numerical results and discussions. The summary is shown in the last section.

2 The quark delocalization color screening model (QDCSM)

The detail of QDCSM used in the present work can be found in the references [24, 25, 26, 27, 28]. Here, we just present the salient features of the model. The model

Hamiltonian is:

$$\begin{aligned}
H &= \sum_{i=1}^6 \left(m_i + \frac{p_i^2}{2m_i} \right) - T_c + \sum_{i<j} V_{ij}, \\
V_{ij} &= V^G(r_{ij}) + V^\chi(r_{ij}) + V^C(r_{ij}), \\
V^G(r_{ij}) &= \frac{\alpha_s}{4} \lambda_i \cdot \lambda_j \left[\frac{1}{r_{ij}} - \frac{\pi}{2} \delta(r_{ij}) \left(\frac{1}{m_i^2} + \frac{1}{m_j^2} \right. \right. \\
&\quad \left. \left. + \frac{4\sigma_i \cdot \sigma_j}{3m_i m_j} \right) - \frac{3}{4m_i m_j r_{ij}^3} S_{ij} \right], \\
V^\chi(r_{ij}) &= \frac{\alpha_{ch}}{3} \frac{\Lambda^2 m_\chi}{\Lambda^2 - m_\chi^2} \left\{ \left[Y(m_\chi r_{ij}) - \frac{\Lambda^3}{m_\chi^3} Y(\Lambda r_{ij}) \right] \right. \\
&\quad \left. \sigma_i \cdot \sigma_j + \left[H(m_\chi r_{ij}) - \frac{\Lambda^3}{m_\chi^3} H(\Lambda r_{ij}) \right] S_{ij} \right\} \\
&\quad \mathbf{F}_i \cdot \mathbf{F}_j, \quad \chi = \pi, K, \eta \\
V^C(r_{ij}) &= -a_c \lambda_i \cdot \lambda_j [f(r_{ij}) + V_0], \\
f(r_{ij}) &= \begin{cases} r_{ij}^2 & \text{if } i, j \text{ occur in the same} \\ & \text{baryon orbit} \\ \frac{1 - e^{-\mu_{ij} r_{ij}^2}}{\mu_{ij}} & \text{if } i, j \text{ occur in different} \\ & \text{baryon orbits} \end{cases} \\
S_{ij} &= \frac{(\sigma_i \cdot \mathbf{r}_{ij})(\sigma_j \cdot \mathbf{r}_{ij})}{r_{ij}^2} - \frac{1}{3} \sigma_i \cdot \sigma_j.
\end{aligned} \tag{1}$$

Where S_{ij} is quark tensor operator; $Y(x)$ and $H(x)$ are standard Yukawa functions [30]; T_c is the kinetic energy of the center of mass; α_{ch} is the chiral coupling constant, determined as usual from the π -nucleon coupling constant; α_s is the quark-gluon coupling constant. In order to cover the wide energy range from light to heavy quarks one introduces an effective scale-dependent quark-gluon coupling $\alpha_s(\mu)$ [31]:

$$\alpha_s(\mu) = \frac{\alpha_0}{\ln\left(\frac{\mu^2 + \mu_0^2}{\Lambda_0^2}\right)}, \tag{2}$$

where μ is the reduced mass of two interacting quarks. All other symbols have their usual meanings. Here, a phenomenological color screening confinement potential is used, and μ_{ij} is the color screening parameter. For the light-flavor quark system, it is determined by fitting the deuteron properties, NN scattering phase shifts, $N\Lambda$ and $N\Sigma$ scattering phase shifts, respectively, with $\mu_{uu} = 0.45$, $\mu_{us} = 0.19$ and $\mu_{ss} = 0.08$, satisfying the relation, $\mu_{us}^2 = \mu_{uu} * \mu_{ss}$. When extending to the heavy quark case, there is no experimental data available, so we take it as a common parameter. In the present work, we take $\mu_{cc} = 0.01 \text{ fm}^{-2}$ and $\mu_{uc} = 0.067 \text{ fm}^{-2}$, also satisfy the relation $\mu_{uc}^2 = \mu_{uu} * \mu_{cc}$. All other parameters are also taken from our previous work [28], except for the charm and bottom quark masses m_c and m_b , which are fixed by a fitting to the masses of the charmed

and bottom mesons. The values of those parameters are listed in Table 1. The corresponding masses of the baryons and charmed and bottom mesons are shown in Table 2.

Table 1 Model parameters: $m_\pi = 0.7 \text{ fm}^{-1}$, $m_k = 2.51 \text{ fm}^{-1}$, $m_\eta = 2.77 \text{ fm}^{-1}$, $\Lambda_\pi = 4.2 \text{ fm}^{-1}$, $\Lambda_k = 5.2 \text{ fm}^{-1}$, $\Lambda_\eta = 5.2 \text{ fm}^{-1}$, $\alpha_{ch} = 0.027$.

b (fm)	m_s (MeV)	m_c (MeV)	m_b (MeV)	a_c (MeV fm ⁻²)
0.518	573	1675	5086	58.03
V_0 (MeV)	α_0	Λ_0 (fm ⁻¹)	μ_0 (MeV)	
-1.2883	0.5101	1.525	445.808	

Table 2 The masses of the baryons and charmed and bottom mesons (in MeV).

	N	Δ	Λ	Σ	Σ^*	Ξ
QDCSM	939	1232	1118	1224	1358	1365
Exp.	939	1232	1116	1193	1385	1318
	Ξ^*	Ω	D	D^*	B	B^*
QDCSM	1499	1654	1865	1900	5279	5290
Exp.	1533	1672	1864	2007	5279	5325

The quark delocalization in QDCSM is realized by specifying the single particle orbital wave function of QDCSM as a linear combination of left and right Gaussians, the single particle orbital wave functions used in the ordinary quark cluster model,

$$\begin{aligned}
\psi_\alpha(\mathbf{s}_i, \epsilon) &= (\phi_\alpha(\mathbf{s}_i) + \epsilon \phi_\alpha(-\mathbf{s}_i)) / N(\epsilon), \\
\psi_\beta(-\mathbf{s}_i, \epsilon) &= (\phi_\beta(-\mathbf{s}_i) + \epsilon \phi_\beta(\mathbf{s}_i)) / N(\epsilon), \\
N(\epsilon) &= \sqrt{1 + \epsilon^2 + 2\epsilon e^{-s_i^2/4b^2}}.
\end{aligned} \tag{3}$$

$$\begin{aligned}
\phi_\alpha(\mathbf{s}_i) &= \left(\frac{1}{\pi b^2} \right)^{3/4} e^{-\frac{1}{2b^2}(\mathbf{r}_\alpha - \mathbf{s}_i/2)^2} \\
\phi_\beta(-\mathbf{s}_i) &= \left(\frac{1}{\pi b^2} \right)^{3/4} e^{-\frac{1}{2b^2}(\mathbf{r}_\beta + \mathbf{s}_i/2)^2}.
\end{aligned}$$

Here \mathbf{s}_i , $i = 1, 2, \dots, n$ are the generating coordinates, which are introduced to expand the relative motion wavefunction [25]. The mixing parameter $\epsilon(\mathbf{s}_i)$ is not an adjusted one but determined variationally by the dynamics of the multi-quark system itself. This assumption allows the multi-quark system to choose its favorable configuration in the interacting process. It has been used to explain the cross-over transition between hadron phase and quark-gluon plasma phase [32].

3 The Results and Discussions

Here, we investigate the ND systems with $I = 0$ and 1, $J^P = \frac{1}{2}^\pm$, $\frac{3}{2}^\pm$, and $\frac{5}{2}^\pm$. For the negative parity states,

the orbital angular momentum L between clusters is set to 0; and for the positive parity states, $L = 1$. All the channels involved are listed in Table 3. The channel coupling calculation is also performed. However, we find there is no any bound state with the positive parity in our calculations. In the following we only show the results of the negative parity states.

Table 3 The channels involved in the calculation.

$I = 0, S = 1/2$	$ND,$	ND^*	
$I = 0, S = 3/2$	ND^*		
$I = 1, S = 1/2$	$ND,$	$ND^*,$	ΔD^*
$I = 1, S = 3/2$	$ND^*,$	$\Delta D,$	ΔD^*
$I = 1, S = 5/2$	ΔD^*		

Because an attractive potential is necessary for forming bound state or resonance, we first calculate the effective potentials of all the channels listed in Table 3. The effective potential between two colorless clusters is defined as, $V(s) = E(s) - E(\infty)$, where $E(s)$ is the energy of the system at the separation s of two clusters, which is obtained by the adiabatic approximation. The effective potentials of the S -wave ND systems with $I = 0$ and $I = 1$ are shown in Fig. 1 and 2, respectively. From Fig. 1(a), we can see that the potential of the $J^P = \frac{1}{2}^-$ channel ND is weak attractive, while for the channel ND^* , the potential is repulsive and so no bound state can be formed in these two single channels. However, the attractions of $J^P = \frac{3}{2}^- ND^*$ is much larger as shown in Fig. 1(b), which means that two hadrons, N and D^* , could be bound together in this case. For the effective potentials of the $I = 1$ system as shown in Fig. 2, the attractions are large for all ΔD^* channels, as well as the $J^P = \frac{3}{2}^- \Delta D$ channel, followed by the $J^P = \frac{1}{2}^- ND^*$ channel, the potential of which is very weak, while for both $J^P = \frac{1}{2}^- ND$ and $J^P = \frac{3}{2}^- ND^*$ channels, the potentials are repulsive.

In order to check whether the possible bound states can be realized, a dynamic calculation is needed. Here the RGM equation is employed. Expanding the relative motion wavefunction between two clusters in the RGM equation by gaussians, the integro-differential equation of RGM can be reduced to an algebraic equation, the generalized eigen-equation. The energy of the system can be obtained by solving the eigen-equation. In the calculation, the baryon-meson separation ($|s_n|$) is taken to be less than 6 fm (to keep the matrix dimension manageable). The binding energies and the masses of every single channel and those with channel coupling are listed in Table 4.

For the $I = 0, J^P = \frac{1}{2}^-$ system, the single channel calculation shows that the energy of ND is above its

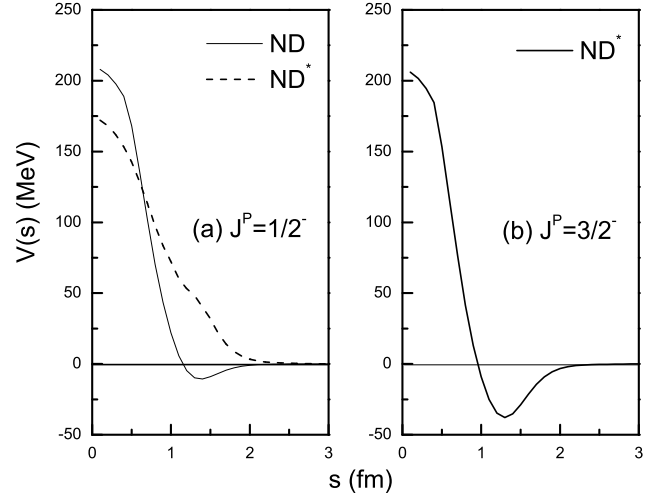


Fig. 1 The potentials of different channels for the ND system with $I = 0$.

threshold although there is a weak attraction between N and D . It is unbound (labeled as "ub" in Table 4), and the ND^* is also unbound, because the interaction between N and D^* is repulsive as mentioned above. However, by taking into account the channel-coupling effect, we obtain a stable state, the mass of which is lower than the threshold of ND . The binding energy and the mass of this bound state is shown in Table 4, which is labeled as "c.c.". First, we should mention how we obtain the mass of a bound molecular pentaquark. Generally, the mass of a molecular pentaquark can be written as $M^{the.} = M_1^{the.} + M_2^{the.} + B$, where $M_1^{the.}$ and $M_2^{the.}$ stand for the theoretical masses of a baryon and a meson respectively, and B is the binding energy of this molecular state. In order to minimize the theoretical errors and to compare calculated results to the experimental data, we shift the mass of molecular pentaquark to $M = M_1^{exp.} + M_2^{exp.} + B$, where the experimental masses of baryons and mesons are used. Taking this bound state as an example, the calculated mass of pentaquark is 2801.6 MeV, then the binding energy B is obtained by subtracting the theoretical masses of N and D , $2801.6 - 939.0 - 1864.6 = -2.0$ (MeV). Adding the experimental masses of the hadrons, the mass of the pentaquark $M = 939.0 + 1864.0 + (-2.0) = 2801.0$ (MeV) is arrived. Secondly, we find that the mass of this bound state is close to the mass of the observed $\Sigma(2800)$, which was reported by Belle collaboration. Therefore, in our quark model calculation $\Sigma(2800)$ can be explained as a ND molecular state with the quantum number $J^P = \frac{1}{2}^-$. Finally, the coupling between the S -wave ND and ND^* channels, which is through the central force, is of crucial importance for obtaining a bound state here. In order to see the strength of these

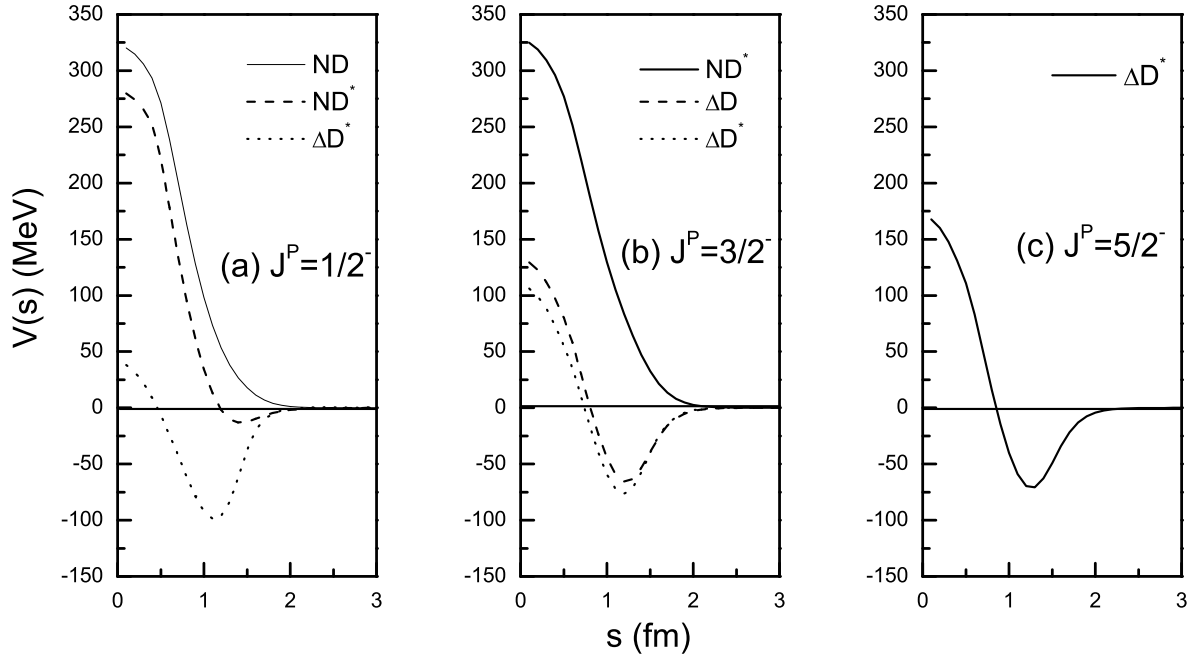


Fig. 2 The potentials of different channels for the ND system with $I = 1$.

Table 4 The binding energies (E_B) and the masses (M) (in MeV) of every single channels and those of channel coupling ($c.c.$) for the ND system.

		ND	ND^*	ΔD	ΔD^*	$c.c.$
$IJ^P = 0\frac{1}{2}^-$	E_B/M	$ub/2803$	$ub/2946$	$-/-$	$-/-$	$-2.0/2801.0$
$IJ^P = 0\frac{3}{2}^-$	E_B/M	$-/-$	$-5.7/2940.3$	$-/-$	$-/-$	$-5.7/2940.3$
$IJ^P = 1\frac{1}{2}^-$	E_B/M	$ub/2803$	$ub/2946$	$-/-$	$-25.3/3213.7$	$ub/2803$
$IJ^P = 1\frac{3}{2}^-$	E_B/M	$-/-$	$ub/2946$	$-14.7/3081.3$	$-18.5/3220.5$	$ub/2946$
$IJ^P = 1\frac{5}{2}^-$	E_B/M	$-/-$	$-/-$	$-/-$	$-28.9/3210.1$	$-28.9/3210.1$

channel-coupling, we calculate the transition potential of these two channels, which is shown in Fig. 3(a). Obviously, it is a strong coupling among these channels that makes ND the bound state. This mechanism to form a bound state has been proposed before. Eric S. Swanson proposed that the admixtures of $\rho J/\psi$ and $\omega J/\psi$ states were important for forming $X(3872)$ state [33], which was also demonstrated by T. Fernández-Caramés and collaborators [34]. The mechanism also applied to the study of H -dibaryon [35], in which the single channel $\Lambda\Lambda$ is unbound, but when coupled to the channels $N\Xi$ and $\Sigma\Sigma$, it becomes a bound state.

For the $I = 0$, $J^P = \frac{3}{2}^-$ system, it includes only one channel ND^* , and it is a bound state with the mass of 2940.3 MeV, which is close to the mass of $\Lambda_c(2940)^+$. Therefore, in our quark model calculation, $\Lambda_c(2940)^+$ can be explained as a ND^* molecular state with the quantum number $J^P = \frac{3}{2}^-$. This result is consistent with the conclusion of Ref.[13], in which they proposed

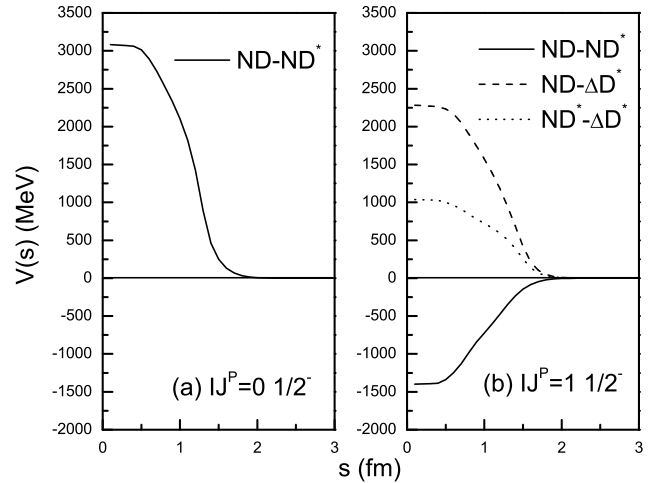


Fig. 3 The transition potentials of different channels for the ND system.

Table 5 The binding energies (E_B) and the masses (M) (in MeV) of every single channels and those of channel coupling (*c.c.*) for the NB system.

		NB	NB^*	ΔB	ΔB^*	<i>c.c.</i>
$IJ^P = 0\frac{1}{2}^-$	E_B/M	$ub/6218$	$ub/6264$	$-/-$	$-/-$	$-3.2/6214.8$
$IJ^P = 0\frac{3}{2}^-$	E_B/M	$-/-$	$-3.4/6260.6$	$-/-$	$-/-$	$-3.4/6260.6$
$IJ^P = 1\frac{1}{2}^-$	E_B/M	$ub/6218$	$ub/6264$	$-/-$	$-14.5/6542.5$	$ub/6218$
$IJ^P = 1\frac{3}{2}^-$	E_B/M	$-/-$	$ub/6264$	$-13.5/6497.5$	$-8.7/6548.3$	$ub/6264$
$IJ^P = 1\frac{5}{2}^-$	E_B/M	$-/-$	$-/-$	$-/-$	$-26.1/6530.9$	$-26.1/6530.9$

that the $\Lambda_c(2940)^+$ could be explained as isoscalar S -wave or P -wave D^*N systems with $J^P = \frac{3}{2}^-$ or $J^P = \frac{1}{2}^+$ in the framework of the one boson exchange model. Meanwhile, a constituent quark model calculation also supported the existence of $\Lambda_c(2940)^+$ as a molecular state composed by nucleon and D^* mesons with $J^P = \frac{3}{2}^-$ [15].

For the $I = 1$, $J^P = \frac{1}{2}^-$ system, the ND is unbound because of the repulsive interaction between N and D as shown in Fig. 1(a). And for ND^* channel, the attraction is too weak to tie the two particles together, so it is also unbound. Due to the stronger attraction, the energy of ΔD^* is below its threshold, so the standalone ΔD^* is a bound state here. Then, we do a channel-coupling calculation. The results show that no stable state can be obtained, i.e., all the energies obtained are higher than the threshold of ND , which indicates that the channel-coupling effect is not strong enough to make ND bound here. The transition potential of these three channels are shown in Fig. 3(b), and we find they are smaller than the one of $I = 0$, $J^P = \frac{1}{2}^-$ ND and ND^* channels, which is shown in Fig. 3(a). Moreover, coupling to the ND and ND^* channels, the energy of state ΔD^* is pushed above its threshold, thus preventing a resonance from materializing.

For the $I = 1$, $J^P = \frac{3}{2}^-$ system, the results are similar with those of the $I = 1$, $J^P = \frac{1}{2}^-$ system. The ND^* is unbound due to the repulsive potential between N and D^* as shown in Fig. 2(b). Both the standalone ΔD and ΔD^* states are bound because of the strong attractions between the corresponding two hadrons. However, these two states disappear by coupling to the ND^* channel.

For the $I = 1$, $J^P = \frac{5}{2}^-$ system, there is only one channel ΔD^* , its energy, 3210.1 MeV, is below the corresponding threshold. It is a good resonance state after coupling to ND by means of tensor interaction. This result is consistent with the one of Ref [36], in which they showed that the ΔD^* with $I = 1$, $J^P = \frac{5}{2}^-$ was an attractive state, presenting a resonance close to threshold by means of a chiral constituent quark model.

Because of the heavy flavor symmetry, we also extend the study to the bottom case of NB system, the numerical results for which are listed in Table 5. The results are similar to the ND system. From Table 5, we find there are several interesting states: a NB bound state with $I = 0$, $J^P = \frac{1}{2}^-$ by two channels (NB and NB^*) coupling; a NB^* resonance state with $I = 0$, $J^P = \frac{3}{2}^-$; and a ΔB^* resonance state with $I = 1$, $J^P = \frac{5}{2}^-$.

4 Summary

In summary, we perform a dynamical calculation of the ND systems with $I = 0$ and 1, $J^P = \frac{1}{2}^\pm$, $\frac{3}{2}^\pm$, and $\frac{5}{2}^\pm$ in the framework of QDCSM. Our results show: (1) All the positive parity states are unbound in our calculation. (2) The pure ND with $I = 0$, $J^P = \frac{1}{2}^-$ is unbound, but a bound state with mass of 2801.0 MeV can be obtained by coupling the ND^* channel. The mass of this bound state is close to the observed $\Sigma(2800)$, which shows that $\Sigma(2800)$ can be explained as a ND molecular state with the quantum number $J^P = \frac{1}{2}^-$ in our quark model calculation. (3) The ND^* with $I = 0$, $J^P = \frac{3}{2}^-$ is also a resonance state with the mass of 2940.3 MeV, closing to the mass of $\Lambda_c(2940)^+$, which indicates that $\Lambda_c(2940)^+$ can be explained as a ND^* molecular state with the quantum number $J^P = \frac{3}{2}^-$ in QDCSM. (4) The $I = 1$, $J^P = \frac{5}{2}^-$ ΔD^* is also a resonance state with mass of 3210.1 MeV. Besides, the calculation is also extended to the bottom case of NB system. The results are similar to the case of the ND system. On the experimental side, confirming the existence of the charmed hadrons $\Sigma(2800)$ and $\Lambda_c(2940)^+$ is an interesting subject. Besides, searching for other molecular states with heavy quarks, such as ΔD^* , NB , NB^* and ΔB^* will be challenging topics in future.

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